

# **Determination of Vertical Refractivity Structure from Ground-based GPS Observations**

Principal Investigator: Christian Rocken  
Co-Principal Investigator Sergey Sokolovskiy  
GPS Science and Technology  
University Corporation for Atmospheric Research  
Boulder, CO 80301  
Phone: 303 497 8012 fax: 303 497 2610 email: [rocken@ucar.edu](mailto:rocken@ucar.edu)

Award Number: N00014-00-C-0258

## **LONG-TERM GOAL**

The goal of this multi-year project is to develop GPS remote sensing techniques for the determination of atmospheric signal delay, refractive bending, and refractivity structure to aid in sensing of the refractive environment of ships or land-based stations.

## **SCIENTIFIC OBJECTIVES**

The primary scientific objective of this research is to develop GPS sounding techniques for ground based atmospheric refractivity sensing. Atmospheric profiling with GPS from space has been demonstrated (e.g. Rocken *et al.*, 1997). Ground based receivers have been used to determine integrated atmospheric water vapor above a site, but profiling techniques with ground-based GPS observations are still under development (Anderson 1982, 1994). Ground based observations of GPS tropospheric signal delay and bending cannot be inverted to high-resolution atmospheric profiles comparable to radiosondes, but they provide direct measurements of microwave signal bending (Sokolovskiy *et al.*, 2001) and coarse refractivity structure information (Lowry *et al.*, 2002). Space based radio occultation data may also be useful for the detection of sharp refractivity gradients (Sokolovskiy, 2002).

## **APPROACH**

We are pursuing a three-step approach to reach the long-term goal of refractivity profiling with GPS from a ship.

- (1) Develop and test GPS single slant measurement techniques
- (2) Develop techniques to interpret these slant measurements
  - (a) Determination of profile information & signal bending
- (3) Develop a system for a mobile platform
  - (a) Evaluation and development of precise kinematic positioning
  - (b) Field tests – Flip-ship (FLIP) experiment
  - (c) Ocean ship-board experiment

During the last year our efforts were focussed on ocean-based experiments. We processed the data collected during a new 7-day experiment aboard the Explorer of Seas (Explorer) in the Caribbean in

<b>Report Documentation Page</b>			<i>Form Approved OMB No. 0704-0188</i>	
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>				
1. REPORT DATE <b>30 SEP 2003</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2003 to 00-00-2003</b>		
4. TITLE AND SUBTITLE <b>Determination of Vertical Refractivity Structure from Ground-based GPS Observations</b>				
6. AUTHOR(S)				
5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER				
5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>GPS Science and Technology, University Corporation for Atmospheric Research,,Boulder,,CO,80301</b>				
8. PERFORMING ORGANIZATION REPORT NUMBER				
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				
10. SPONSOR/MONITOR'S ACRONYM(S)				
11. SPONSOR/MONITOR'S REPORT NUMBER(S)				
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>9</b>
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	19a. NAME OF RESPONSIBLE PERSON	

July of 2002 and conducted a repeat experiment in August 2003. We continued improving software for GPS cycle slip detection and repair at extremely low observation elevation angles. We compared ship positions with known geoid models, tidal models and sea surface height measurements from the TOPEX/Poseidon altimeter.

Validation of results from the '02 Explorer cruise is difficult because we do not have ground truth for the ship's position and we have only several radiosonde launches for comparison with GPS zenith precipitable water vapor (PWV) estimates and with GPS profiles. The repeat experiment in '03 was conducted because a microwave water vapor radiometer (WVR) was operated aboard the ship, which will allow verification of the GPS estimates of PWV. During the first cruise we also failed to collect any observations at negative elevation, a problem that was remedied during the repeat experiment. Also a large section of the second cruise was traveled on a very similar track to and from the island of St. Thomas. We hope that this repeat track will give us an additional measure of how well GPS on a ship can estimate sea surface height and the Geoid.

High resolution vertical refractivity profiling is feasible from space with the GPS radio occultation technique. In the moist tropical atmosphere it is often impossible to track the occulting GPS satellite to near the surface because of atmospherically induced fluctuations on the signals phase and amplitude. These fluctuations are so sever that they cannot be tracked by phase locked loop. We have very similar problems with tracking near-horizon GPS signals on the ground. For space based tracking improvements so called open-loop tracking was proposed. The same technique should be used for future ground based experiment. This however requires that open loop tracking receivers are developed for ground-based applications. We are investigating the requirements for ground based open loop tracking.

## WORK COMPLETED AND RESULTS

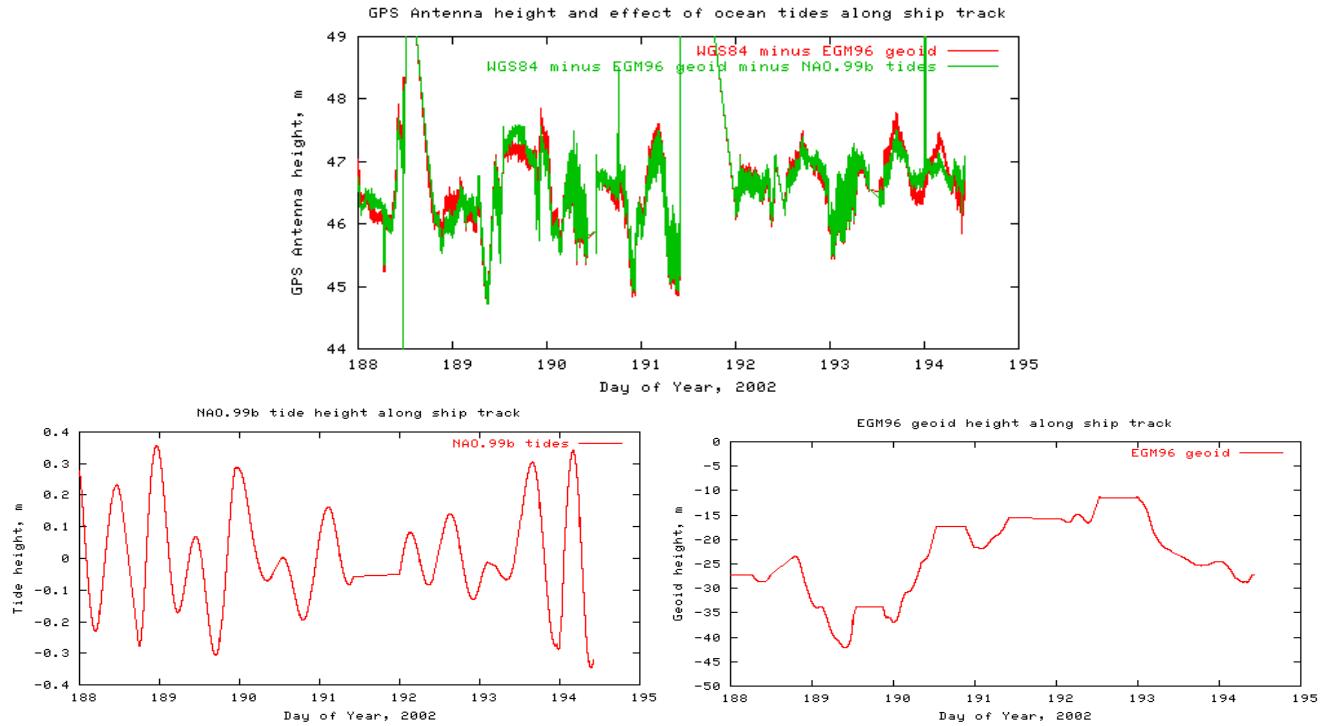
Progress was made in (1) processing of observations collected during the '02 Explorer experiment; (2) validation of the results from the first experiment; (3) preparation and carrying out of the second '03 sea-going experiment aboard Royal Caribbean's Explorer of the Seas; (4) preliminary analysis of the data collected during the '03 experiment; (5) open loop GPS tracking for ground based GPS receivers. Highlights of the accomplished tasks are summarized below:

**We have processed the data from the first '02 Explorer of the Sea experiment:** First we processed the GPS data to obtain a precise position of the ship along the cruise track. The vertical position varied in a range of ~30 meters. Most of this variation can be attributed to changes in the geoid height. However even after removing the geoid and the tidal variations (using the NAO, 99b tidal model, Matsumoto et al., 2000) along the ships track variations in the range of ~ +/- 0.5 meters remain (Figure 1). This remaining apparent vertical movement could be attributed to many sources: (1) errors in the precise kinematic GPS point position solution, (2) errors in the tidal model, (3) errors in the geoid model, (4) vertical motion of the ship due to changes in mass and dynamic effects. It is important to understand these error sources. Based on kinematic positioning tests with fixed stations on known location we would not expect that more than ~5-10 cm rms would be due to vertical errors of the GPS position. We know that the tidal model is good to ~ 15 cm rms in the part of the ocean where our cruise took place. We do not have a good estimate of changes in the ship's vertical position due to dynamic or mass changes. However it is feasible that some of the apparent vertical motion may be actual geoid signal.

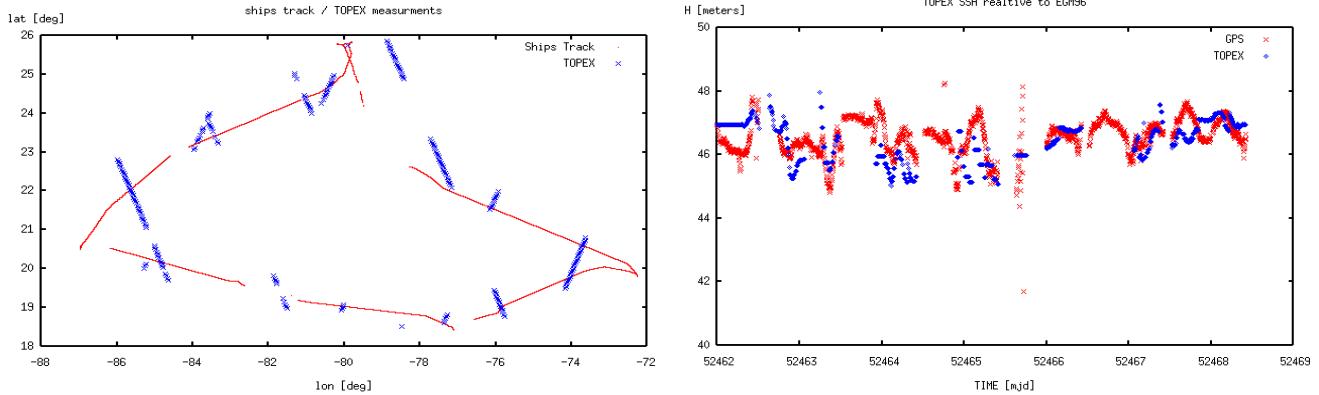
It is important to note that our primary objective - refractivity profiling from a ship will be affected by the 5-10 cm rms GPS position error. The other errors due to tidal mode, geoid, and ship have no effect

on this objective. They are important though for assessing the ultimate value of precise GPS positions from a ship in the open ocean.

We compared the vertical position residuals against Topex Poseidon measurements near the ship's track: In an effort to explain the remaining vertical position fluctuations in Figure 1 we compared obtained Topex/Poseidon observations from the time of our experiment. Figure 2 shows the comparison of the satellite altimeter measurements with vertical ship positions after both (the Topex/Poseidon and GPS observations) had been corrected for Geoid and tidal fluctuations. The correlation between the data is not very good. This could be due in part because only few Topex/Poseidon observations really coincide spatially close with the ship's track and because the Topex /Poseidon observations were taken at different times (Figure 2).

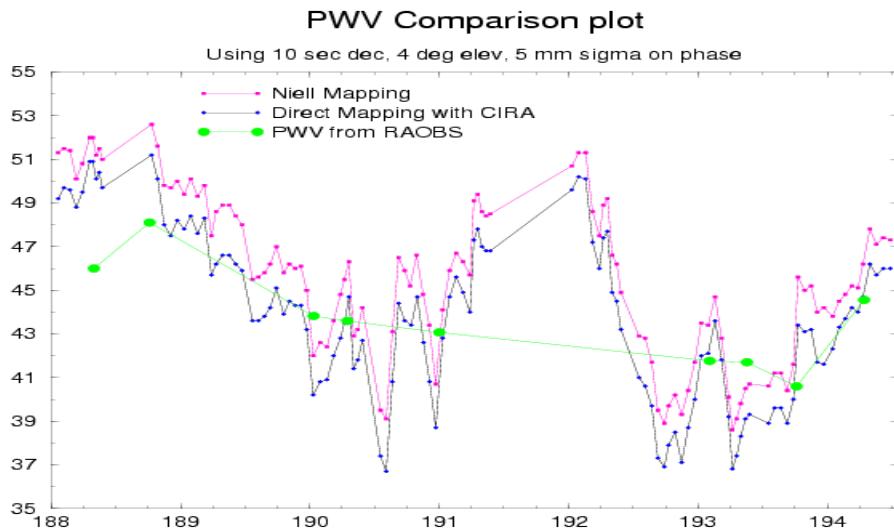


*Figure 1: The top panel shows a time series for the entire '02 cruise of the vertical position of the ship based on our GPS results. In red we show the results after removal of the EGM96 geoid (lower right panel geoid along ship's track), in green we show the results after removing the geoid and the tides (lower left panel shows tides along the ship's track for the cruise).*



**Figure 2:** The left panel shows the locations of the Topex/Poseidon altimeter measurements (blue crosses) and the ship's track (red lines) for the '02 cruise. The right panel compares the ship's vertical position after Geoid and tidal model correction and the Topex altimeter ocean heights (also after geoid and tidal model removal and biased to coincide with the first GPS point). In general there is only little correlation between the two time series.

**We compared the estimated tropospheric wet delay computed from GPS with radiosonde data:** In order to obtain refractivity or bending angle profiles it is important to determine accurate positions of the receiving antenna. Accurate positions depend on how well the tropospheric delay can be estimated from the GPS data. We determined the delay due to the dry part of the troposphere from barometric pressure measurements taken on the ship and estimated the remaining "wet delay" due to atmospheric water vapor from the GPS data every three hours. The wet delay was converted to precipitable water vapor (PWV). We also computed PWV from 9 radiosondes that were launched during the cruise. In Figure (3) we compare GPS PWV from two different solutions with radiosonde PWV. The two different solutions use two different mapping functions for the a priori hydrostatic delay: (1) Niell mapping which is the standard used in high accuracy GPS data analysis; and (2) direct mapping which was developed under this grant and described in previous reports (Rocken 2001).

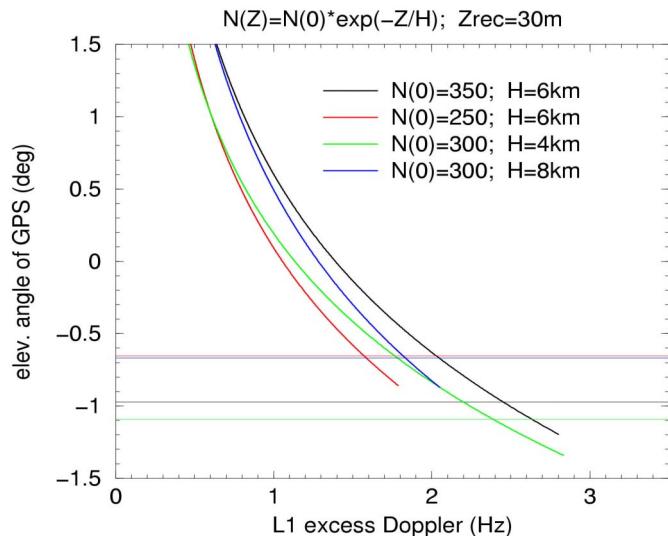


**Figure 3** Comparison GPS PWV estimates from two different solutions (magenta with the Niell mapping function and blue with the "Direct Mapping") with radiosonde values for the 2002 cruise.

**Tracking GPS signals at low elevations by a geodetic GPS receiver often results in loss of lock.**

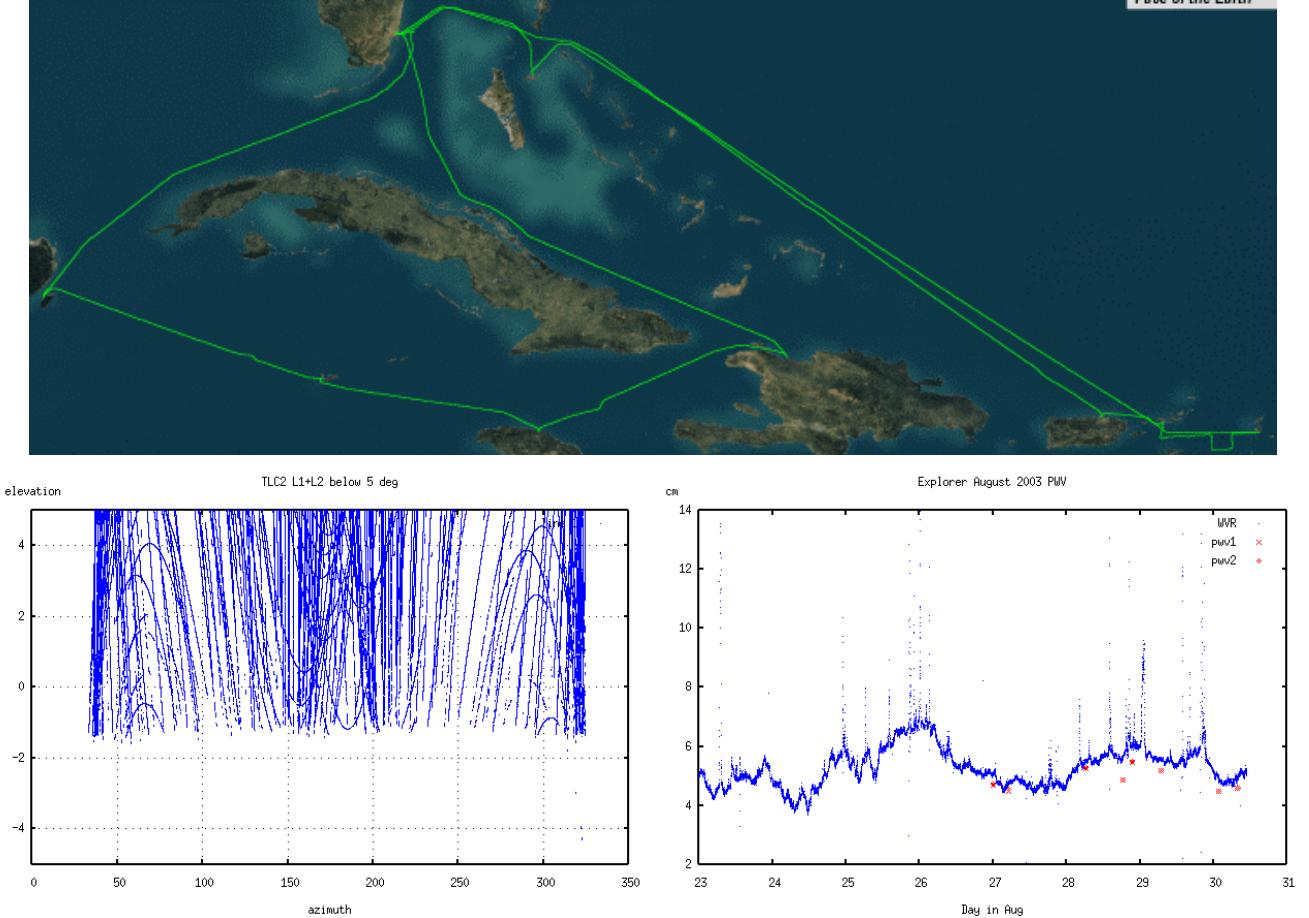
This is the most troublesome problem for this research project and the biggest obstacle to obtaining good data from satellites that are setting behind the ocean horizon. Sometimes the receiver continues tracking after missing data during an extended time interval but in most cases the phase is connected incorrectly (contains integer number of cycle ambiguities). The loss of lock happens most often when tracking over the sea, when the signal reflected from sea water is close in frequency and amplitude to the direct signal, resulting in deep fading of the amplitude. In a geodetic GPS receiver the phase is projected ahead for the next update interval based on extrapolation of the previously extracted phase (Stephens S.A., J.B.Thomas, 1995). Reduction of the signal amplitude close to or below the noise level results in big errors of the phase extraction from the complex signal (I and Q) and in big deviation of the extrapolated phase model from the true phase. This, in turn, results in further increase of errors of the phase extraction and in further reduction of the signal to noise ratio (due to the integration of I and Q applied in the receiver).

It is feasible to modify the receiver firmware so that below a certain GPS elevation angle, instead of using feedback for extrapolation of the phase (phase-locked loop) the receiver uses a phase model based on a predicted GPS orbit (open loop). Figure 1 shows the L1 Doppler frequency shift (in excess to that in a vacuum) estimated by raytracing for an exponential refractivity model and a receiver height of 30 m until the ray hits the surface. Horizontal lines show the elevation angle below which the ray tangent point is lower than the height of the receiver. Without other error sources one could expect that the GPS signal downconverted with the frequency model based on GPS orbit and refractivity climatology, sampled at 1 Hz rate, would allow reconstruction of the connected phase in the postprocessing. However, other error sources (a dominant source seems to be the receiver clock error) can introduce an additional frequency mismodelling in the receiver and 1 Hz sampling frequency may be insufficient. On the other side, 10 Hz sampling frequency would allow open loop tracking with a phase model based on only on the predicted GPS orbit. We believe that such tracking will be required to fulfill the promise of surface-based refractivity sensing from a ship.



**Figure 4 Simulation of atmospheric Doppler frequency for several exponential refractivity profiles with different atmospheric scale heights and different surface refractivities as a function of the geometric angle to the observed GPS satellite. Horizontal lines show the elevation angle below which the ray tangent point is lower than the height of the receiver.**

We prepared and conducted a repeat experiment in August 2003. The cruise track and initial data analysis results are shown in Figure 5. We are now working on the GPS analysis for this experiment.



**Figure 5.** Top panel shows the cruise tracks of the '02 (west) and '03 (east) cruise tracks. The bottom left panel shows that we tracked a significant number of satellites to  $\sim 1.5$  degrees. The right panel shows the WVR measurements of PWV in cm (blue line) during the 7-day cruise and the corresponding radiosonde-derived PWV values (red dots).

## IMPACT/APPLICATION

Remote sensing of atmospheric features and refractivity profiles with GPS promises to impact Navy communication and sensing capabilities and to provide a new data set for improved numerical weather prediction. Ground based determination of bending angles using GPS has the potential for aiding in locating exo-atmospheric targets. Precise kinematic point positioning to conduct these activities from a moving platform (ship) seems feasible and may also lead to precise timing on ships. Precise kinematic point positioning from ships may also provide additional data for Geoid improvements in the oceans. Estimation of precipitable water vapor from ships seems feasible and may aid in weather forecasting. This study lead to the discovery of the effect that superrefraction has on the inversion of radio occultation profiles. This is an extremely important discovery that will help us to keep refractivity profiles, affected by superrefraction, from corrupting numerical weather prediction in the future.

## TRANSITIONS

The company "Trex Enterprises" of San Diego California is planning to develop a product that utilizes technology developed under this grant for the detection of atmospheric bending angles from ground based GPS observations. (<http://www.trexenterprises.com/>) and an SBIR phase I appears to have been awarded related to this technology:

[http://www.winbmdo.com/scripts/sbir/abstract.asp?log=1060&Phase=1&Ph1Yr=03&firm\\_id=5098&int=031](http://www.winbmdo.com/scripts/sbir/abstract.asp?log=1060&Phase=1&Ph1Yr=03&firm_id=5098&int=031))

## RELATED PROJECTS

- 1) This study lead to the discovery of the effect that superrefraction in the COSMIC project. COSMIC is a project to launch 6 atmospheric/ionospheric sensing satellites in 2005 that is funded jointly by Taiwan and the U.S. U.S. co-sponsors include NSF, NOAA, NASA, and ONR.
- 2) The Department of Energy is continuing to fund UCAR to develop low-cost L1-only GPS systems for tropospheric tomography. This study requires the measurement of single transmitter - receiver slant ranges, the same GPS observable required for refractivity profiling.
- 3) NCAR, NOAA and scientists in Europe and Japan are working on assimilation of PWV and single GPS slant measurements into numerical weather models. The slant measurement techniques that we are developing with this study can then be applied to numerical weather forecasting. Ship-based PWV may also be of value for weather models.
- 4) Georgia Tech. has submitted a joint patent application with UCAR for determination of GPS bending based on ground based observations.
- 5) The mapping function that was developed for this project (we called it Direct Mapping but the term "Dynamic Mapping" is more commonly used) has been applied to processing all the data from the Japanese 1000+ station GPS network by the Japanese scientist Dr. T. Iwabuchi.

## PATENTS

UCAR has submitted a joint patent with Georgia Tech. for the measurements of atmospheric bending angles from the ground using GPS observations.

## REFERENCES

Alber, C. R. Ware, C. Rocken, and J. Braun, Inverting GPS double differences to obtain GPS single path phase delays, *Geophys. Res. Lett.*, 27, 2661-2664, 2000.

Anderson, K. D., Inference of refractivity profiles by satellite-to-ground RF measurements, *Radio Science*, Vol. 17, Num. 3, pp 653-663, 1982.

Anderson, K. D., Tropospheric refractivity profiles inferred from low-elevation angle measurements of Global Positioning System (GPS) signals, *AGARD Conf. Proc.*, AGARD-CP-567-2, Sep 19-22, Bremerhaven, Germany, 1994.

Braun, J., C. Rocken, and R. Ware, Validation of line-of-sight water vapor measurements with GPS, *Radio Science*, Vol. 36, No. 3, p. 459, May 2001.

Lowry, A. R., C. Rocken, and S. Sokolovskiy, Vertical Profiling of refractivity from ground-based GPS, *Radio Science*, Vol. 37, No. 3, pp 13.1 - 13.10, 2002.

Matsumoto, K., T. Takanezawa, and M. Ooe, Ocean Tide Models Developed by Assimilating TOPEX/POSEIDON Altimeter Data into Hydrodynamical Model: A Global Model and a Regional Model Around Japan, *Journal of Oceanography*, 56, 567-581, 2000.

Rocken, and co-authors, Verification of GPS/MET data in the neutral atmosphere, *J. Geophys. Res.*, 102, 29,849-29,866, 1997.

Rocken, C., J. M. Johnson, J. Braun, H. Kawawa, Y. Hatanaka, T. Imakiire, Improving GPS Surveying with modeled Ionospheric Corrections, *Geophys. Res. Lett.* Vol. 27, No. 23, p. 3821, 2000.

Rocken, C., S. Sokolovskiy, J. M. Johnson, and D. Hunt, Improved Mapping of Tropospheric Delays, *J. Atm. Ocean. Tech.*, Vol. 18, No. 7, 1205-1213, July 2001.

Sokolovskiy, S. V., C. Rocken, A. R. Lowry, The use of GPS for estimation of bending angles of radio waves at low elevations, *Radio Science*, Vol. 36, No. 3, p. 473 2001 (a).

Sokolovskiy, S.V., Tracking tropospheric radio occultation signals from low Earth orbit, *Radio Science*, Vol. 36, No. 3, pp 483-498, 2001.

Sokolovskiy, S., Effect of super refraction on inversions of radio occultation signals in the lower troposphere. Submitted to *Radio Science*, 2002.

Stephens S.A., J.B.Thomas, Controlled root formulation for digital phase-locked loops, *IEEE Trans. on Aerospace and Electron. Syst.*, 31(1), 78-95, 1995).

## PUBLICATIONS (2002 / 2003)

Lowry, A. R., C. Rocken, and S. Sokolovskiy, Vertical Profiling of refractivity from ground-based GPS, *Radio Science*, Vol. 37, No. 3, pp 13.1 - 13.10, 2002.

Sokolovskiy, S., Effect of superrefraction on inversions of radio occultation signals in the lower troposphere. *Radio Science*, Vol. 38, No.3, 2003.